Options for increasing the productivity of the rice-wheat system of north-west India while reducing groundwater depletion. Part 1. Rice variety duration, sowing date and inclusion of mungbean

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ABSTRACT

The irrigated rice-wheat (RW) systems of north-west India are critical for food security. However, these systems are not sustainable due to over-exploitation of the groundwater resource on which they largely rely. Current farmer practice (FP) involves manual transplanting of rice into heavily tilled/puddled soil from 10 June to early July, prolonged periods of flooding, rice residue burning, and heavy tillage prior to sowing wheat. Inclusion of a short duration mungbean crop between wheat harvest and rice transplanting has also been promoted at times. Options for reducing irrigation input to the RW system include delaying transplanting until after the monsoon rains start (late June), switching to shorter duration rice varieties, and alternate wetting drying (AWD) water management for rice. However, the effect of such practices on groundwater depletion is not well-understood. Examining the effects of these options on cropping system yield and components of the water balance and water productivity is highly complex because of the need to consider the interactions between each crop in the system. Therefore, we used a cropping system model (APSIM) to compare the performance of RW systems with a range of rice transplanting dates (4 dates from 10 June to 10 August) and rice variety durations (long - 158 d, medium - 144 d, short - 125 d), with and without mungbean in the system. The results suggest that changing from long to short duration varieties would reduce ET by around 250 mm, more than enough to halt the groundwater decline, but with a reduction in rice-equivalent system

yield of about 2.5 t ha⁻¹ compared with current FP. On the other hand, inclusion of mungbean into the RW system results in much higher system yield than recommended farmer practice (by over 3 t ha⁻¹), but the tradeoffs are much higher ET (by 250 to 300 mm) and irrigation requirement (by 300 to 450 mm). The results of this study suggest that more effort should be directed towards the development of higher-yielding, short duration rice varieties to reduce groundwater depletion of the RW system while maintaining yield, and that inclusion of short duration summer crops such as mungbean should not be recommended.

1. Introduction

The RW systems of South Asia are important for food security of the region (Timsina and Connor, 2001), and for the livelihoods of the many millions of farming families and others employed in aspects of the value chain. Most of the RW area is located on the Indo-Gangetic Plains (IGP), with 10 Mha in India, 2 Mha in Pakistan, 0.5 Mha in each of Nepal and Bangladesh. The two small north-west Indian states of Punjab and Haryana, located mostly in the Indus Basin, provide about half the rice and 85% of the wheat procured by the Indian government. The RW system in this region is almost entirely dependent on groundwater for irrigation (Ambast et al., 2006), however, current rates of groundwater extraction are not sustainable (Humphreys et al., 2010).

The hydrogeology of the north-west IGP of India and impacts of cropping system intensification on groundwater levels were briefly reviewed by Humphreys et al. (2010). In short, the green revolution in the 1960s and 70s led to a huge increase in groundwater pumping as rice and wheat production expanded and intensified. As a result, watertables declined and continue to decline at an alarming rate. While the falling watertable incurs greater pumping costs for

farmers, the main threat to sustainability is intrusion of saline groundwater into the fresh groundwater as a result of changed pressure gradients. Therefore, there is an urgent need for technologies that reduce water use of the RW system. A wide range of “water saving” technologies has been developed which reduce irrigation input to rice and/or wheat. The most promising of these technologies include delayed rice transplanting, changing to shorter duration rice varieties, and changing from continuous flooding to alternate wetting and drying (AWD) water management for rice (Humphreys et al., 2010). However, whether and to what degree these technologies will reduce groundwater depletion is questionable (Humphreys et al., 2010). At the same time, there is interest in the inclusion of a short duration mungbean crop between wheat harvest and rice establishment, to increase both land productivity and the production of pulses, and because crop diversification can be beneficial to help break disease and weed cycles. However, little thought has been given to the consequences for groundwater depletion of introducing an additional crop during the hot, dry summer period. Furthermore, determination of the impacts of changing practices on productivity and water use at the cropping system scale has received little attention to date.

Water is lost from farmers’ fields as transpiration (T) via the plants, evaporation from the soil or from water lying on the soil surface (E), vertical drainage beyond the root zone (“deep drainage”), and surface runoff in times of excessive rains. Irrigation application to rice in this region greatly exceeds that needed to meet evapotranspiration (ET) requirement because of the practice of keeping the fields ponded for prolonged periods, together with the permeable nature of the soils, leading to large amounts of deep drainage. However, water draining beyond the root zone ultimately returns to the groundwater which is pumped for irrigation, thus drainage is not a loss from the soil-groundwater system in this region (Ahmad et al., 2014). Hence, reducing

irrigation requirement by reducing deep drainage alone will not reduce groundwater depletion. To reduce groundwater depletion, reduction in ET is required (Ahmad et al., 2014; Humphreys et al., 2010). But biomass production and thus yield are positively related to T (e.g. Haefele et al., 2009), so reduction in T is likely to lead to reduction in yield, and T is likely to increase if yields are increased, unless transpiration efficiency is increased. In the short term, there is little scope for substantial increase in the transpiration efficiency of rice and wheat (Passioura and Angus, 2010; Sheehy, 2000). At present there are major efforts to provide a large increase in the transpiration efficiency of rice by transforming rice from a C3 to a C4 plant, however, if successful, it will be many years before C4 rice varieties will be available (Caemmerer et al., 2012). Therefore the most useful way to reduce ET is by reducing E, although this may be compensated for to some degree by an increase in T as a result of a change in the microclimate of the crop canopy (less humid due to less E) (Balwinder-Singh et al., 2011c).

Examining the effects of changing rice variety duration, planting date and water management on the land productivity of the total system, and on components of the water balance and water productivity, is highly complex because of the interactions between each crop in the system. For example, rice variety duration and sowing date affect the date of rice harvest and thus the time when wheat can be sown. This in turn affects both the yield and water requirement of wheat, and also the window available for growing a legume between wheat harvest and rice establishment. These interactions are also affected by seasonal conditions. For example, a cool grain filling period for rice prolongs grain filling and thus duration of rice, possibly delaying wheat sowing. Likewise, a cool grain filling period for wheat delays sowing of mungbean. Use of a cropping system model provides the opportunity to account for such interactions, and to examine performance both of individual crops and the total system under the

weather conditions experienced over many years. This in turn introduces the possibility of developing a probabilistic understanding of outcomes. Therefore, we used the APSIM model with the specific objectives of evaluating: (i) the ability of APSIM to simulate the RW system of north-west India using conventional crop establishment methods, (ii) the effects of rice variety duration, planting date and water management on the performance of the RW system, and (iii) the effects of including a short duration mungbean crop. Comparisons were made for individual crops and for the total system in terms of yield, components of the water balance, and water productivity. The ultimate objective was to identify cropping system management options with the potential to halt the groundwater decline in north-west India, whilst maintaining or increasing food production. In Part 2 (Balwinder-Singh et al., 2014), we explore the potential of conversion to conservation agriculture to achieve the same objectives.

2. Materials and methods

The APSIM model was used to explore the impacts of changing rice variety duration, planting date and water management, and inclusion of a legume, on the performance of a RW cropping system using conventional crop establishment methods. The simulations were performed using 40 years (1970-2010) of daily weather data from the meteorological station at Punjab Agricultural University (PAU), Ludhiana. Performance was compared in terms of grain yield of individual crops, total system productivity (rice equivalent yield), components of the water balance, and water productivity. Rice equivalent yield was determined using the prices paid to farmers for rice (1,250 Rs kg⁻¹), wheat (1,350 Rs kg⁻¹) and mungbean (4,400 Rs kg⁻¹) in 2012. Rice equivalent yield (kg ha⁻¹) of the non-rice crops was calculated as non-rice yield (kg ha⁻¹) ×

non-rice price (Rs kg⁻¹)/rice price (Rs kg⁻¹). The components of the water balance examined were irrigation amount, evapotranspiration (ET), deep drainage beyond 180 cm (the maximum rooting depth of wheat), and runoff. Water productivity was computed with respect to ET (WP_{ET}) and irrigation (WP_i) in terms of kg grain ha⁻¹mm⁻¹ for individual crops, and for the total system using rice equivalent yield.

2.1 The APSIM model (v 7.3)

APSIM is a simulation modelling framework that enables sub models to be linked to simulate agricultural system performance (Keating et al., 2003). The sub models include specific crop modules, for example WHEAT, ORYZA and MUNGBEAN, soil water (SOILWAT), soil nitrogen (SOILN) and surface residue (SURFACE ORGANIC MATTER). The crop modules simulate crop development, growth, water and N uptake, N concentration, stresses (water deficit, N deficit, aeration deficit) and the response of the crop to the stresses. The descriptions of these specific modules can be found elsewhere (Asseng et al., 2002; Balwinder-Singh et al., 2011a;). The WHEAT module is based on CERES Wheat (Ritchie et al., 1985) but with modifications (Asseng et al., 1998; Probert et al., 1995; Wang et al., 2003; Huth, unpublished). The MUNGBEAN module is based on Robertson et al. (2002). The rice crop module (ORYZA) is based on rice crop physiology adapted from the ORYZA2000 model (Bouman and van Laar, 2006). The APSIM framework was recently enhanced to allow simulation of transitional soil C and N dynamics for rotations which involve flooded rice and other non-flooded crops, such as RW rotations (Gaydon et al., 2012a). Algorithms to facilitate simulation of the important long-term inputs of C and fixed N from pond organisms (such as algae) in rice-based systems were also added (APSIM-Pond module; Gaydon et al., 2012b).

2.2 Model parameterisation, calibration, and validation

The model was parameterised for rice, wheat and mungbean grown on a sandy loam soil in north-west India. The soil parameters were based on the properties of a field site at Punjab Agricultural University (PAU), Ludhiana (Humphreys et al., 2008; Yadvinder-Singh et al., 2009) (Table 1). The soil had a plant available water capacity (PAWC) of 110 mm over the 0-60 cm soil profile, and a PAWC of 290 mm over the 0-180 cm soil profile. The stage 1 soil evaporation parameter (U) was set to 10 mm, and the stage 2 parameter (cona) was set to 2 mm, based on the values used by Arora et al. (2007) and Timsina et al. (2008). The saturated percolation rate was set to 20 and 6 mm d⁻¹ for non-puddled and puddled soil, respectively, based on the observations of Humphreys et al. (2008).

The phenological parameters were derived and response functions were adjusted in the APSIM-ORYZA, WHEAT and MUNGBEAN modules using data from experiments conducted at PAU. Phenological parameters were derived for 3 rice varieties of different duration: PR118 (158 d) and PR115 (125 d) using the data of Yadvinder-Singh et al. (2009), and PAU201 (144 d) using the data of Sudhir-Yadav et al. (2011a,b; 2012). To capture the effect of low temperature on rice spikelet sterility (important for later sowing of longer duration varieties), spikelet sterility is calculated in ORYZA according to Horie et al. (1992) based on the ‘cooling degree days’ concept using threshold temperature 22°C. The default average daily temperature threshold in the model was changed from 22°C to 28°C based on the results of the field study of Nagarajan et al. (2010) conducted in a similar environment with similar rice varieties. The rice crop was killed when mean daily temperature was below 12°C for 3 consecutive days. The phenological parameters for the wheat variety PBW343 were derived for non-mulched and mulched conditions using the data of Balwinder-Singh et al. (2011b,c). For mulched conditions, the

parameters were derived so that anthesis was delayed by about 6 d compared with the non-mulched crop as APSIM does not include processes to simulate the effects of mulch on soil temperature and crop phenological development. In the current version of APSIM WHEAT, phenology is based on cumulative thermal degree days. Thermal time units increase linearly with increase in daily average temperature from 0 to 24°C, with a maximum value at 24°C which then decreases linearly to 0 at 34°C. However, this approach was unable to accurately simulate the phenology of late planted wheat crops whose growth period falls into temperatures higher than the optimum of 24°C. After reviewing the literature and discussions with wheat physiologists, we modified this approach by retaining thermal time accumulation at a maximum for temperatures between 24 and 34°C, declining thereafter to zero at 40°C, similar to the approach used in DSSAT (Jones et al., 2002, Ken Boote, personal communication). We tested the approach against available data (Ortiz-Monastero et al., 1994; RK Sharma, unpublished data) and the modified model performed sensibly in simulating wheat crop duration under high temperature. The phenology parameters of mungbean cultivar SML668 were derived using the data of Gathala et al. (2014). The parameterized and calibrated model was then successfully validated by comparing simulated and measured yield and soil volumetric water content for independent data sets from the above experiments.

2.3 Simulations

2.3.1 Cropping system scenarios

All cropping system scenarios involved farmer practice (FP) crop establishment methods - puddled transplanted rice (PTR) followed by conventional tillage and wheat sowing by seed drill (CTW).

The following scenarios were compared:

- (i) Farmer practice (FP): PTR-CTW-fallow, with farmer planting and water management

- (ii) Recommended farmer practice (rFP): PTR-CTW-fallow as in (i), but with recommended planting and water management
- (iii) Recommended farmer practice plus mungbean (rFP+mung): PTR-CTW-mung, as for (ii), but with mungbean replacing the long fallow between wheat harvest and rice planting

2.3.2 *Simulation variables*

Within each of the three cropping system scenarios, the effects of changing rice sowing date, rice variety duration, and replacement of the fallow by mungbean, were evaluated.

Rice variety duration

The performance of the cropping system was compared for three rice varieties with long (PR118, 158 d), medium (PAU201, 144 d) and short (PR115, 125 d) duration. Most farmers grow long duration varieties such as PR118, or varieties with similar duration to PR118 (Sudhir-Yadav et al., unpubl. data).

Rice sowing date

Four rice sowing dates were compared by sowing the seedling nurseries at 20-21-d intervals starting on 15 May. The rice was transplanted 30 and 25 d after sowing in the FP and rFP scenarios, respectively. In Punjab, transplanting is prohibited prior to 10 June (Singh, 2009), hence the choice of 15 May as the first sowing date, resulting in 10 June transplanting for rFP. About 80% of the rice area in Punjab is transplanted by 30 June (S.S. Kukal, pers. comm.), the date of transplanting for the 2nd sowing date with rFP.

Fallow/mungbean

216 The effect of replacing the long fallow between wheat harvest and rice transplanting with a
217 mungbean crop was also compared. Mungbean is a short duration (~65 d) legume which can
218 normally fit in the time available between wheat harvest and rice sowing in RW systems with
219 long duration rice transplanted in June.

220 **2.3.3 Crop management**

221 All crops were grown with nutrients non-limiting in all simulations.

222 *Rice establishment*

223 The soil was flooded one day before transplanting and one disking and two tyne harrowings were
224 done on the same day. In the FP scenario, plant density was 25 hills m⁻² with one plant hill⁻¹ and
225 30 day-old seedlings, consistent with the results of surveys of farmer practice in Punjab (Sudhir
226 Yadav et al., unpubl. data). In the rFP scenario, plant density was 33 hills m⁻² with 2 plants hill⁻¹
227 and 25 day-old seedlings, according to recommended practice (Anonymous, 2012a).

228 *Rice water management*

229 The 40-year simulations commenced with the soil profile full of water at the time of
230 establishment of the first rice crop in 1970. On the day of puddling in subsequent years, the
231 amount of water applied was that required to fill the top three soil layers (0-30 cm) to saturation
232 plus an additional 50 mm of water to create a surface pond for puddling. The amount applied
233 depended on the dryness of the soil, which varied depending on whether there was a bare fallow
234 or an irrigated mungbean crop prior to the rice crop, as well as on the weather prior to rice
235 establishment.

236 Typical farmer irrigation management for PTR in Punjab involves keeping the field
237 flooded for the first 1-2 months after transplanting, followed by alternate wetting and drying
238 (AWD, irrigating once the topsoil becomes dry). Therefore, for the FP simulations, a pond depth

of 50 mm was maintained for the first 50 d after transplanting by irrigating daily when needed. After that, irrigations were applied whenever the average matric suction of the 0-20 cm layer rose to around 20 kPa. Water management for rFP was similar except that ponding was maintained for only 15 d after transplanting (recommended practice). At each irrigation, the amount of water applied was that required to saturate the 0-30 cm soil profile plus an additional 50 mm of water to create a temporary surface pond. Irrigation of rice in all systems ceased about one week before crop maturity, and the rice was harvested eight d after physiological maturity to allow time for grain moisture content to decline to less than 20% as occurs in practice, as there is a market price penalty for higher moisture content.

Wheat management

Wheat was sown following rice straw removal and conventional tillage. The rice straw was not removed until six days after harvest, as the residues are still moist at the time of harvest, and it takes a few days before the straw is dry enough to burn. Almost all the rice straw is burnt in Punjab. Straw removal was immediately followed by one irrigation of 75 mm, and four days later tillage commenced (one discing and two harrowings to a depth of 10 cm over a period of five days). The effect of tillage on soil roughness and thus runoff and water retained on the soil surface and available for infiltration was captured by changing the USDA curve number, by 10 in the case of each discing, and by 5 for harrowing (Littleboy et al., 1996a,b). The curve number was reset to the default curve number when at least 40 mm of water was added to soil (by rain or irrigation) to simulate the collapse/smoothing of a freshly cultivated soil surface as a result of saturation and rainfall impact (Littleboy et al., 1996a,b). The wheat was sown 15 d after rice harvest, but not before 1 November, because early sowing is detrimental to yield. Wheat variety PBW343 (155 d duration) was sown with a plant density of

200 plants m⁻², 20 cm row spacing and 5 cm depth in all systems. The wheat was irrigated whenever soil water deficit (SWD) increased to 50% in the 0-60 cm soil profile. The amount of irrigation water applied was 120% of SWD in an attempt to represent the inherent inefficiency of flood irrigation. The wheat was harvested eight days after physiological maturity to allow time for the grain to dry in the field.

Mungbean management

The field was irrigated (60 mm) three days after wheat harvest to allow time to harvest the wheat straw, the majority of which is normally collected for fodder, with the rest burnt. Two days after irrigation, mungbean (var. SML668, duration ~65 d) was drilled at plant density of 100 plants m⁻², row spacing 20 cm, sowing depth 10 cm. Thereafter, the mungbean was irrigated based on 70% SWD of the 0-60 cm soil profile with an irrigation amount equivalent to 120% of SWD. There was no irrigation beyond 55 days after sowing (DAS). In situations where the mungbean had not fully reached physiological maturity by the time of puddling for rice, the mature mungbean pods were harvested two days before puddling. All the mungbean residues were left on the soil surface and incorporated during tillage for rice.

3. Results

3.1 Model validation

The calibrated and parameterized RW cropping system model performed well, as evidenced by its ability to predict yields of rice varieties of different duration (root mean square error (RMSE 200 kg ha⁻¹) (Fig. 1), and by the dynamics of volumetric water content from harvest of wheat in 2005 through the subsequent rice crop and up to sowing of the next wheat crop (RMSE 0.007 cm³ cm⁻³) (Fig. 2). The validation for mungbean was also satisfactory, with a RMSE of 560 kg ha⁻¹ for total biomass and 230 kg ha⁻¹ for grain yield. Evidence of the good performance of

APSIM WHEAT (in terms of wheat yield, biomass accumulation over time and soil water dynamics) for this location is also provided in Balwinder-Singh et al. (2011a). In the case of rice, Sudhir-Yadav et al. (2011b, 2012) showed that ORYZA2000 performs well in the same environment for simulation of PTR under flooded conditions and for AWD with irrigation scheduled when volumetric soil water content of the 0-20 cm layer declines to 20 kPa. Furthermore, Gaydon et al. (unpubl. data) showed that APSIM-ORYZA performs well for simulation of PTR with continuous flooding and AWD in various rice growing regions in South Asia.

3.2 Cropping system scenarios

The effects of rice variety duration and sowing date on the performance of the RW system are first presented using farmers' practice (FP), and the findings are then compared with the results using improved farmers' practice (rFP). The results for the RW-mung (RWM) systems (rFP+mung) are then compared with the results of FP and rFP.

The only parameters significantly affected by changing from FP to rFP were components of the water balance (see below) due to the change from flooding for the first 50 d after transplanting to flooding for only the first 15 d. The crop compensated for the wider plant spacing with FP by producing more tillers (as nutrient supply was non-limiting), and the effects of the wider spacing and the five days delay in transplanting in FP compared with rFP on grain yield, components of the water balance and water productivity were negligible and are not discussed further.

3.2.1 Yield

Rice yield varied greatly depending on seasonal conditions, with much greater variation for later sowing of the long and medium duration varieties (Fig. 3a). For example, under FP with the

earliest sowing (15 May) of the shortest duration variety (PR115) yield ranged from 3.5 to 6.6 t ha⁻¹, while yield of the longest duration variety (PR118) sown on 20 June ranged from 2.5 to 10.0 t ha⁻¹ (Fig 3a). In contrast, the effect of sowing date on yield was very small for the short duration variety. Yield of both the long and medium duration varieties increased as sowing was delayed from 15 May to 5 June, with a further increase in yield with delay to 20 June for the medium duration variety. However, 20 June sowing of the long duration variety resulted in low yields in many years, and further delay to 15 July sowing resulted in yields of only 0 to 3.5 t ha⁻¹. Similarly, 15 July sowing of the medium duration variety resulted in yields of less than 2.6 t ha⁻¹ in 50% of years. Rice yield trends and absolute values with rFP and rFP+mung were very similar to those for FP (data not presented).

Yields of wheat were slightly to considerably lower than yields of the long duration rice variety for the first three sowing dates, with differences in median yields of 0.7 to 2.0 t ha⁻¹ (Fig. 3a). The variation in wheat yield was usually greater than the variation in rice yield within rice variety × sowing date combinations. Median wheat yields were generally in the range 5.2 to 6.5 t ha⁻¹. The exceptions were the lower yields of wheat following late sown (15 July) long and medium duration rice. Wheat yields with rFP and rFP+mung were very similar to those with FP for respective rice variety × sowing date combinations (data not presented).

Mungbean yields with the first rice sowing date were often very low with all rice varieties because of premature harvest of the mungbean (Fig. 3b). The consistently highest mungbean yields were with June and July sowings of the medium and short duration rice varieties.

System yields of FP and rFP were similar (Tables 2a-c), and trends in total system yield (rice equivalent yield) were similar to trends in rice yield. For example, mean rice equivalent

yield of the rFP RW system with long duration rice increased from 13.6 to 14.4 t ha⁻¹ as sowing date was delayed from 15 May to 5 June and declined to 12.5 and 5.7 t ha⁻¹ with 20 June and 15 July sowings, respectively, due to reduced rice and/or wheat yield (Table 2a). In contrast, with the short duration variety, rice equivalent system yield was similar for all four sowing dates (mean yields 11.8 to 12.3 t ha⁻¹) (Table 2c). System rice equivalent yields with rFP+mung were higher than with FP and rFP in respective variety × sowing date treatment combinations, with mean yield usually in excess of 15 t ha⁻¹, whereas median yield of FP and rFP was always less than 15 t ha⁻¹. For example, with rFP, the highest mean system yield was 14.6 t ha⁻¹ with 5 June sowing of the long duration variety, compared with 17.2 t ha⁻¹ with mungbean added. For maximum system yield, the best options were 5 June sowing of the long duration rice variety and 5 and 20 June sowings of the medium duration variety in the rFP+mung systems.

3.2.2 Irrigation water input

Irrigation input to rice also varied greatly depending on seasonal conditions (Fig. 4a). In contrast to yield, the variation was generally greatest for earlier sowings, more so for the long and medium duration varieties. For example, with FP, irrigation input to the long duration rice variety sown on 15 May ranged from 830 to 1780 mm, and the range narrowed to 1000 to 1610 mm for 15 July sowing (Fig 4a). Median irrigation input increased from 1130 to 1375 mm as sowing date of the long duration variety was delayed from 15 May to 15 July. The effect of sowing date on median irrigation input was smaller for the medium and short duration varieties, but irrigation input was always highest for the last sowing. Median irrigation input decreased with varietal duration (within sowing date), and was always lower with the short than the long duration rice variety, regardless of sowing date. Irrigation input with rFP was around 200 mm

lower than with FP within sowing date $\times$ variety combinations, but with similar trends in terms of effects of variety and sowing date on irrigation amount.

Irrigation applications to wheat were also highly variable, but were far lower than to rice, with median values ranging from 215 to 270 mm, and with relatively small effects of rice sowing date or varietal duration (Fig. 4b). There was a slight increase in median irrigation amount of about 50 mm with delay in sowing from 15 May to 15 July regardless of rice varietal duration in the rotation, because with later rice sowing, the latter part of the wheat season was pushed into a period of higher evaporative demand.

Mungbean irrigation input was also highly variable, and was generally least for the latest rice sowings (Fig. 4b) due to the resultant delay in mungbean sowing which ultimately pushed the mungbean growth period into more humid weather with lower evaporative demand and a greater likelihood of rain.

Trends in total irrigation application to the RW system closely mirrored trends in application to rice for FP and rFP. Within sowing date, irrigation amount decreased with varietal duration in all three systems (Tables 2a-c). Mean irrigation amount with FP (1720 mm) was highest with 15 July sowing of the long duration variety, and least with 5 and 20 June sowings of the short duration variety (1240 mm). Irrigation amount was around 200 mm lower with rFP than FP in respective treatment combinations. The lowest mean values with rFP were 1040 and 1035 mm for 5 and 20 June sowings, respectively, of the short duration variety. Adding mungbean to the system increased irrigation input within respective rice variety $\times$ sowing date combinations by around 200 to 450 mm. Mean irrigation input with rFP+mung was usually around or above 1500 mm except for June and July sowings of the short duration variety (means 1360 to 1420

mm). Thus, for minimum system irrigation input, the best scenarios were rFP with the short duration variety sown any time between 15 May and 15 July.

3.2.3 Drainage

Under FP, the median amount of drainage beyond the root zone during the rice crop ranged from about 580 to 855 mm (Fig. 5a), compared to only 10-40 mm from the wheat crop and 0 to 50 mm during the long fallow between wheat harvest and rice transplanting (Fig 5b). The amount and variability of drainage from rice increased with delay in sowing. Decreasing rice variety duration had little effect on the amount of drainage except for the last sowing date. The effects of sowing date and variety duration on drainage from rice with rFP were similar to those with FP, however the amount of drainage from rFP was lower, with median values reduced by 130 to 200 mm. Drainage from rice was further reduced by about 20 mm under the rFP+mung system for May and June sowings. There was no significant drainage during the mungbean crop.

Trends in total RW system drainage strongly reflected trends in rice drainage. The amount of drainage and its variability generally increased with delay in transplanting for all rice varieties, more so as duration increased, and more so with FP than rFP. For example, drainage with long duration rice variety in the FP system ranged from 560 to 880 mm for the earliest sowing date, and from 750 to 1350 mm with the latest sowing date (Tables 2a-c). Varietal duration had only a small effect on reducing the amount of drainage for early sowings, and the effect increased slightly as sowing was delayed. Mean drainage decreased from 670 to 660 mm as duration decreased from long to short for the earliest sowing, and from 995 to 780 mm for the latest sowing (Tables 2a-c).

Both the amount of drainage and its variability were lower with rFP within respective sowing date $\times$ variety combinations. For example, for 5 June sowing of the long duration variety,

total drainage ranged from 580 to 920 mm under FP, which was reduced to 420 to 750 mm with rFP. Averaged over the four sowing dates, mean values of total drainage were reduced by 160, 155, 135 mm with long, medium and short duration rice varieties, respectively, with rFP. System drainage losses were least with earlier sowings of all rice varieties using rFP. Adding mungbean to the system had only a small effect on total system drainage, with total drainage reduced by an average of 20 mm compared to rFP for May and June sowings, and by 50 mm for 15 July sowing.

3.2.4 *ET*

Under FP, ET of rice was highest (550 to 1040 mm) with early sowing of the long duration variety and least (385 to 600 mm) with late sowings of the short duration variety (Fig. 6a). The magnitude of ET and/or its variation declined with delay in sowing, more so for the long and medium duration varieties. ET of wheat was lower than ET of rice. The effects of rice varietal duration and sowing date on ET of wheat were relatively small (medians ranged from 390 to 470 mm). The magnitude of and trends in ET of rice and wheat in rFP were similar to those of FP (data not presented).

ET during the long, hot fallow between wheat harvest and rice transplanting increased with delay in rice sowing and to a very slight degree with decrease in rice variety duration (Fig. 6b). Fallow ET ranged from a low of 30 to 140 mm with early sowing of the long duration variety to a high of 130 to 260 mm with late sowing of the short duration variety.

Mungbean ET was highly variable, and was highest for June sowings of all rice varieties (Fig. 6b). Median values ranged from about 255 to 365 mm, compared with only 70 to 190 mm for fallow ET.

Total RW system ET includes ET throughout the cropping system year, i.e. during all crops and the fallow periods between each crop. Total system ET with FP decreased with decreasing rice variety duration. Mean ET of FP ranged from 1250 to 1310, 1170 to 1240 and 1040 to 1150 mm with the long, medium and short duration varieties in the system, respectively (Tables 2a-c). Within variety, the effect of sowing date on system ET was relatively small; the biggest variation occurred with the short duration variety where ET increased as sowing was delayed from 5 June (mean 1040 mm) to 15 July (mean 1150 mm).

The absolute values and trends in ET of rice and wheat, and of the total system, were very similar for FP and rFP, however, variability was less with rFP (Tables 2a-c). RW system ET was least with the short duration variety sown in May or June, using rFP. Adding mungbean to the rFP system increased ET by 80-385 mm in comparison with rFP, with mean values in the range 1295 to 1545 mm.

3.2.5 WPet

The variability of WPet of rice with FP reflected trends in rice yield, and was very high for the last two sowing dates of the long duration variety, and for the last sowing date of the medium duration variety (Fig. 7a). Late June sowing of the long duration variety resulted in a high probability of low rice WPet, and 15 July sowing resulted in very low WPet in all years. For the medium duration variety, there was a trend for WPet to increase with delay in sowing to late June, while for the short duration variety there was little effect of sowing date except for higher WPet with the latest sowing. WPet was highest (median 11.6 kg ha⁻¹ mm⁻¹) for 15 July sowing of the short duration variety, followed by 20 June sowing of the medium duration variety (median 11.0 kg ha⁻¹ mm⁻¹). WPet of rice in the rFP and rFP+mung systems was similar to that in FP.

WPet of wheat was generally higher than that of rice, and was highest and similar for earlier sowings of all rice varieties (15 May and 5 June), with median values around 14.8 kg ha⁻¹ mm⁻¹ (Fig. 7a). However, WPet of wheat declined greatly with delay in sowing of the long rice duration variety from 15 May to 15 July, and to a lesser extent with delay in sowing of the medium duration variety. Wheat WPet in the rFP and rFP+mung systems was similar to that in the FP system.

WPet of mung was much lower than that of rice and wheat, and was least (median 2.0 kg ha⁻¹ mm⁻¹) for the earliest sowing of all varieties, and similar (~2.7 kg ha⁻¹ mm⁻¹) for all other sowing date x variety combinations (Fig. 7a).

Late sowing of the long and medium duration rice varieties greatly reduced WPet of the total system (Table 2a-c). With FP, highest system means (around 10.8 to 11.2 kg ha⁻¹ mm⁻¹) were achieved with the first two sowings of the long duration variety, the first three sowings of the medium duration variety, and all sowings of the short duration variety. WPet was very similar for FP and rFP (data not presented). Addition of mungbean slightly decreased WPet of the systems with the earliest sowing of all rice varieties, and increased WPet for all other variety x sowing date combinations, more so for 15 July sowing (by 1.2 to 1.6 kg ha⁻¹ mm⁻¹).

In terms of maximizing system WPet, rice varietal duration and sowing date were unimportant, apart from avoiding 15 July sowing of the long and medium duration varieties, and 20 June sowing of the long duration variety, using either FP or rFP. Maximum mean system WPet (12.0 kg ha⁻¹ mm⁻¹) was achieved in rFP+mung with the last sowing of the short duration rice variety, however this was only slightly higher than that of several other treatment combinations.

3.2.6 WPI

Using FP, WPI of rice (range 0 to 9.3 kg ha⁻¹ mm⁻¹) (Fig 8a) was much lower and much less variable than WPI of wheat (range 0 to 25 kg ha⁻¹ mm⁻¹) (Fig 8b). The effects of rice variety duration and sowing date on WPI of rice were relatively small, apart from greatly reduced values with later sowings of the long duration rice variety. Excluding the latter, median values of rice WPI ranged from 6.0 to 6.3 kg ha⁻¹ mm⁻¹ (Fig. 8a). Trends in WPI of rice in rFP were similar to those for FP, but WPI was higher than in FP within respective treatment combinations. Median WPI of the first three sowing dates for all varieties in rFP ranged from 6.1 to 7.3 kg ha⁻¹ mm⁻¹. Adding mungbean to the system had negligible effect on rice WPI.

There was a large decline WPI of wheat as sowing of the long duration rice variety was delayed to 20 June and 15 July, with median values decreasing from 18.3 to 8.8 kg ha⁻¹ mm⁻¹ with delay in sowing from 5 June to 15 July (Fig. 8b). Wheat WPI also declined with 15 July sowing of the medium duration rice variety. Wheat WPI in the rFP and rFP+mung systems was the same as in the FP system.

Mungbean WPI increased with delay in sowing date with all rice varieties (Fig. 8b). For example, mungbean WPI increased from 2.4 to 5.5 kg ha⁻¹ mm⁻¹ with delay in sowing from 15 May to 15 July with the long duration rice variety in the FP system. Within rice variety, mungbean WPI was similar for all sowing dates except 15 July when WPI decreased with variety duration from 5.6 to 3.8 kg ha⁻¹ mm⁻¹.

There was no consistent effect of sowing date on system WPI across varieties. With FP, variation in WPI was generally small (in the range 8.0 to 9.5 kg ha⁻¹ mm⁻¹) for all sowing date x variety combinations, apart from much lower values with 15 July sowing of the long and medium duration rice varieties, and an increased likelihood of lower values with 20 June sowing of the long duration variety (Table 2a-c). System WPI with rFP was higher than with FP for

respective variety x sowing date combinations, by means of 1.1 to 1.9 kg ha⁻¹ mm⁻¹ except for 15 July sowing of the long and medium duration varieties. Adding mungbean to rFP decreased system WPI with May and June sowings of the medium and short duration rice varieties, and with May and 5 June sowing of the long duration variety. System WPI was highest and similar (mean 11.3 to 11.5 kg ha⁻¹ mm⁻¹) with rFP with short and medium duration rice sown in June.

4. General discussion

4.1 Evaluation of the performance of APSIM in simulating the RW cropping system of north-west India

The results of the model simulations were generally consistent with the findings of field experiments and other simulation studies evaluating a range of management practices for individual crops (rice, wheat and mungbean), as outlined below. This increases confidence in the overall applicability of APSIM for RW system simulation in north-west India.

4.1.1 Effect of rice sowing date

The APSIM simulations found that the effect of sowing date on rice yield varied greatly depending on varietal duration. For the long duration variety, delaying sowing to late June resulted in considerable yield decline in some years, and a further delay to 15 July resulted in low yields (0 to 3.5 t ha⁻¹) in all years (Fig. 3a). This was due to low temperature during the reproductive and grain filling stages which resulted in high spikelet sterility, and in crop death in very cool years, consistent with the results of the field experiments of Nagarajan et al. (2010). The results of the simulations are generally consistent with the findings of many field and modeling studies which show that the yield of PTR is relatively stable over a wide range of transplanting dates from early May to mid June, with a yield decline for transplanting after mid

June with medium and long duration varieties (e.g. Hira and Khera, 2000; Jalota et al., 2009; Khepar et al., 1999).

The increase in irrigation input to the long duration variety with delay in sowing (Fig. 4a) was due to crop maturity extending beyond the end of the rainy season. The rainy season normally finishes in mid-September, whereas maturity of the medium and long duration varieties sown on 15 July was delayed until as late as the last week of December and the second week of January, respectively. The higher variability in irrigation amount with earlier sowing of the long and medium duration varieties was largely due to variability in the starting date of the monsoon and thus the requirement for much more irrigation water in years when the monsoon was late.

The model simulations showed a relatively small but steady decline in rice ET with delay in sowing, more so as varietal duration increased (Fig. 6a) Khepar et al. (1999) estimated that ET of medium duration rice between transplanting and harvest (duration 110 d) declined by 100 mm as the date of transplanting was delayed from 16 June to 1 August. The decline in average ET for our medium duration variety under FP scenario was of a similar magnitude (70 mm) with delay in transplanting over a similar period (from 15 June to 20 July). Using ORYZA2000 on a sandy loam at Ludhiana, Arora (2006) also found that ET of continuously flooded rice decreased by about 100 mm as transplanting date (PR114, medium duration variety, 142 days) was delayed from mid June to 1 July.

The model simulations showed small increases in WPet of rice with delay in transplanting of the long and medium duration varieties from 15 June to 5 or 20 July (Fig. 7a), consistent with the findings of the field studies of Brar et al. (2012) and Mahajan et al. (2009) for long and medium duration varieties. The findings are also consistent with the observation that crops exposed to high vapour pressure deficit (as for earlier sowings) have lower photo

assimilation per unit of water consumed and higher respiration due to higher day temperature (Kropff et al., 1993).

4.1.2 Effect of rice variety duration

The simulations showed a small decline in rice yield in changing from the long to the medium duration variety for the 15 May and 5 June sowings, and a larger decline in changing to the short duration varieties for the first 3 sowing dates (Fig. 3). This is consistent with the performance of the coarse grain rice varieties commonly grown in Punjab, for which yield increases with varietal duration (Anonymous, 2012; Brar et al., 2012; Mahajan et al., 2009). The exception is the medium duration variety PAU 201, with a yield potential almost as high as that of PR118 (Anonymous, 2012).

The results of the simulations were also consistent with the findings of field experiments in Punjab which showed significantly lower irrigation input and higher WPI with short duration varieties than long and medium duration varieties (Brar et al., 2012; Mahajan et al., 2009). Using CropSyst, Jalota et al. (2009) found that ET of PTR was reduced by about 70 mm with a short duration high yielding hybrid (RH257, 90 d from transplanting to maturity) in comparison with PR 118 (120 d from transplanting to maturity) for sowing dates from 25 April to 25 June. However, yield of the short duration hybrid was 11 to 16% higher than yield of PR118, which may explain why the reduction in ET was much less than the reduction of around 200 mm in our simulations when changing from PR118 to PR115. Using soil tension-based irrigation scheduling with a similar threshold to our rFP, Jalota et al. (2009) found average reductions in deep drainage of 59 and 74 mm when changing to the short duration variety for 10 May and 25

May sowings, respectively. The reduction drainage in going from PR118 to PR115 for 15 May sowing in our rFP simulations was similar (60 mm).

4.1.3 Effect of wheat sowing date

Later sowing of the long and medium duration rice varieties delayed wheat sowing beyond the optimum sowing window. This resulted in a decline in wheat yield with 15 July sowing of the long and medium duration rice varieties. Several field and modeling studies have shown that the optimum sowing window for maximum yield of PBW343 and other varieties of similar duration is late October to mid November (Arora et al., 2007; Ortiz-Monasterio et al., 1994; Timsina et al., 2008). These studies showed that grain yield decreased at rates ranging from 0.7 to 1.2% per day delay in sowing beyond the optimum date as the grain filling period is pushed into warmer weather. The high variability in wheat yield in our simulations was due to high temperature during the grain filling period reducing yield in some years, especially with 15 July sowing of the long duration rice variety. Our simulations showed that with the short duration rice variety in the system, wheat sowing was within the optimum sowing window in the FP system for all but the last rice sowing date. For the medium duration rice variety, wheat sowing was in the optimum window for the first 2 rice sowing dates, and with the long duration rice variety wheat was only sown on time for the first rice sowing date and about half of the 2nd sowing dates.

4.1.4 Effect of irrigation management for PTR

The model simulations showed no effect of changing from FP to rFP on rice yield. This change involved changing from continuous flooding to AWD water management starting two weeks after transplanting instead of seven weeks after transplanting. Many field experiments in north-

west India also showed that that PTR can be grown with AWD without loss of yield, provided that the degree of soil drying is not too great – soil drying for a maximum of 2 to 4 d, or to a maximum soil water tension of about 20 kPa (e.g. Choudhary, 2007; Hira et al., 2002; Kukal et al., 2005; Sudhir-Yadav et al., 2011). These studies also showed large irrigation water savings (15–40% of the applied water or up to 840 mm) in comparison with continuous flooding, consistent with the results of our model simulations. The magnitude of the reduction in irrigation amount depends on soil type, depth to the watertable and seasonal conditions. The model simulations showed a very large effect of seasonal conditions on irrigation input, for example, irrigation input varied from 830 to 1780 mm with FP for long duration rice sown on 15 May and rainfall during the rice season in those two years was 1075 and 130 mm, respectively.

4.1.5 Mungbean performance

Simulated mungbean yields, ET and WP_{Pet} were in the range reported from field studies in the region (Idnani and Singh, 2006; Pannu and Singh, 1993; Rao and Singh, 2003).

4.2 Optimizing system performance

With current farmer practice (June transplanting of long duration varieties) and recommended irrigation management (rFP), the highest yielding RW system produced 14.6 t ha⁻¹. However, determination of the optimum cropping system depends on which system performance parameters are to be maximized or minimized. On the basis of biophysical performance alone, the objectives of farmers are likely to differ from those of water resource managers. Where land is limiting, it is better for farmers to maximize yield, in which case the rFP+mung system with 5 June sowing of the long duration rice variety (17.4 t ha⁻¹) is the best option, 2.8 t ha⁻¹ higher than the highest yielding rFP system. However, if irrigation water is limiting (either physically or

economically), the best option for the farmer is systems with the highest WPI (Gaydon et al., 2011). Maximum system WPI (mean $11.5 \text{ kg ha}^{-1} \text{ mm}^{-1}$) occurred with rFP with 5 and 20 June sowing of the short duration rice variety, but with much lower yield (average 11.8 to 11.9 t ha^{-1}) and irrigation input (around 1040 mm) than the highest yielding rFP+mung and rFP systems.

From the point of view of a water resource manager in a system where deep drainage returns to the groundwater and is not a loss to the system, as in north-west India, the objective should be to decrease cropping system ET to a level where losses from the groundwater are balanced by recharge (Humphreys et al., 2010). ET of the cropping system was least (mean 1040 mm) with short duration rice sown on 5 June in the FP and rFP systems. This gave a reduction in ET of 255 mm compared with the highest yielding rFP system, but came at the expense of reduction in system yield by an average of 2.8 t ha^{-1} . A reduction in ET of 255 mm is almost double the “back of the envelope” estimate of Humphreys et al. (2010) of the required reduction to halt the groundwater decline in central Punjab. The highest yielding systems which gave a reduction in ET of at least 150 mm in comparison with 5 June sowing of the long duration variety were FP and rFP with the short duration variety, with yield about 2 t ha^{-1} lower than the highest yielding FP and rFP systems.

From the point of view of society, the objective might be to maximize the productivity of the depleted water (WP_{et}) and restrict the cropped area to that required to balance ET and groundwater recharge, in order to meet the increasing requirement for food and to make more water available for other uses. In that case, the optimum system is rFP+mung with the short duration rice variety sown in July, with a WP_{et} of $12.0 \text{ kg ha}^{-1} \text{ mm}^{-1}$ (compared with $11.3 \text{ kg ha}^{-1} \text{ mm}^{-1}$ for the highest yielding rFP system) and a 0.9 t ha^{-1} higher average system yield. However, restricting the cropped area is likely to be unacceptable on socio-economic grounds, difficult to

implement, and the magnitude of the permissible cropped area should also depend on how the non-cropped lands are managed as ET from the fallow lands also needs to be included in the water balance calculations used to estimate the sustainable cropping area in terms of water depletion.

4.3 Implications and the next steps

There is no doubt that ET from RW cropping systems needs to be reduced to the degree that groundwater levels cease to decline, or perhaps even stabilize at a shallower depth below the soil surface. The simulations suggest that ET from the predominant farmer practice (15 May-5 June sowing of long duration varieties) averages 1240 to 1290 mm. Assuming that a reduction in ET of 150 mm is required, the only way to achieve this with current cultural practices in the RW system is by the use of short duration rice varieties, with a reduction in system yield of 2.5 t ha⁻¹ compared with the highest yielding FP systems). This suggests that increasing the yield potential of short duration rice should be a high priority for breeders. Alternatively, the area under cultivation could be reduced and cropping systems intensified, but then the question of use of the vacated lands arises and its impact on ET (among other considerations). The use of alternative crop establishment and management practices in the RW system, such as reduced tillage, dry seeding of rice and mulching should also be considered. Dry seeded rice with safe AWD water management has a lower irrigation requirement than PTR with the same water management (Sudhir-Yadav et al., 2011a), but what are the effects on ET? Sudhir-Yadav et al. (2011b) found similar ET for DSR (conventional tillage) and PTR with the same safe AWD water management (20 kPa irrigation threshold). Direct seeding of wheat into rice residues can greatly reduce the turn around time between rice harvest and wheat sowing, while keeping the residues on the soil surface suppresses soil evaporation (Balwinder-Singh et al., 2011b), both of which might reduce

water depletion. Whether conversion to a conservation agriculture (CA) RW system encompassing all these practices will provide better options for increasing cropping system yield, while reducing ET to a sustainable level, needs to be explored. The impacts of replacement of rice and/or wheat with other crops also needs to be explored. Accurate field determination of ET for current and potential landuses and management is urgently needed to properly evaluate the ability of crop models to predict ET, because it is the primary cause of groundwater depletion. Balwinder-Singh et al. (2014) found deficiencies in the 2-stage model (Ritchie, 1972) commonly used to predict soil evaporation in simulation models including APSIM. Furthermore, spatial hydrologic studies are needed to determine the level of cropping system ET that can actually be sustained across the landscape, and which cropping systems/management will be sustainable in terms of the water balance.

Conclusions

The APSIM model was well able to simulate performance of the RW system in north-west India under typical farmer practice. However, to achieve this, some model processes were adjusted to capture the effects of low temperature on rice, and of high temperature on wheat, to enable reliable simulation of the growth, phenology and yield of late sown rice and wheat. While this was important in terms of capturing the effects on the yield of each crop, it was equally important in terms of the effects on the date of crop maturity because this in turn affected the date of sowing of the next crop in the system, and thus its performance.

Current farmer practice (FP) for RW systems in north-west India involves puddling the soil, sowing of long duration rice varieties from mid-May to early June followed by transplanting from 10 June to early July, prolonged periods of flooding, rice residue burning, and intensive

tillage prior to sowing the following wheat crop. Model simulations with APSIM show that this is a highly productive system, with an average system rice-equivalent yield of 13.6 to 14.4 t ha⁻¹. However, current practice is unsustainable due to over-exploitation of groundwater for irrigation. To halt the decline in groundwater levels, evapotranspiration (ET) must be decreased. Model simulations suggest that ET can be reduced by the theoretical desired amount (~150 mm) by switching from long to short duration rice varieties, with a wide sowing window from mid-May to mid-July. However, this will come at the cost of around 2.5 t ha⁻¹ of rice equivalent yield, and will not be attractive to farmers. The simulations also show that inclusion of mungbean in the RW rotation greatly increases cropping system rice equivalent yield, with a maximum yield of 17.4 t ha⁻¹. However, this comes at the expense of an increase in ET of around 250 to 305 mm compared with the highest yielding RW system, which would further exacerbate the rate of groundwater decline. The results suggest the need for focusing breeding efforts on raising the yield potential of short duration rice varieties. The potential to reduce water depletion while maintaining or increasing system yield using other approaches, such as changing to a conservation agriculture RW system, and replacing rice and/or wheat with other crops, also needs to be explored.

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Table 1 Physical properties of the sandy loam soils used in the simulations

	Sand (%)	Silt (%)	Clay (%)	LL (cm ³ cm ⁻³)	DUL (cm ³ cm ⁻³)	SAT (cm ³ cm ⁻³)	BD (gcm ⁻³)	pH
Sandy Loam								
0-10	65.6	17.2	17.2	0.07	0.26	0.36	1.61	6.7
10-20	66.4	17.3	16.1	0.07	0.26	0.34	1.69	7.0
20-30	67.3	17.4	15.3	0.07	0.27	0.31	1.76	7.3
30-60	71.4	12.0	16.6	0.06	0.23	0.36	1.61	7.6
60-90	72.2	13.0	14.8	0.06	0.21	0.39	1.53	7.7
90-120	73.8	12.2	14.0	0.07	0.21	0.39	1.53	7.8
120-150	80.9	10.9	8.2	0.05	0.21	0.39	1.52	7.8
150-180	88.1	5.3	8.6	0.05	0.20	0.39	1.52	7.8

LL—volumetric water content at lower limit. DUL—volumetric water content at drained upper limit. SAT—volumetric water content at saturation. BD—bulk density

Tables 2a,b,c. Total system yield, components of the water balance and water productivity of farmers' practice (FP), recommended FP (rFP), and recommended FP with mungbean (rFP+mung) for the rice-wheat-mungbean system as affected by rice variety duration and sowing date in central Punjab, India. Data are mean values, range in parentheses. Mean annual rainfall was 742 mm and ranged from 386-1276 mm over the 40 years. WPI is water productivity based on amount of irrigation water applied and WP_{pet} is water productivity based on ET.

2a. Long duration variety (PR118)

	Rice equivalent yield (t ha ⁻¹)	Irrigation (mm)	ET (mm)	Drainage (mm)	Runoff (mm)	WPI (kg ha ⁻¹ mm ⁻¹)	WP _{pet} (kg ha ⁻¹ mm ⁻¹)
15 May Sowing (D1)							
FP	13.6 (8.8-16.3)	1500 (1130-2170)	1250 (950-1610)	670 (560-880)	50 (0-275)	9.1 (6.6-11.9)	10.8 (8.9-13.2)
rFP	13.6 (8.8-16.5)	1310 (960-1930)	1250 (950-1610)	520 (380-695)	40 (0-172)	10.6 (7.7-14.2)	10.9 (9.0-13.3)
rFP+ mung	15.6 (11.4-19.6)	1565 (1165-2285)	1500 (1200-1855)	505 (360-660)	40 (0-172)	10.1 (7.0-13.8)	10.4 (8.6-12.1)
5 June Sowing (D2)							
FP	14.4 (10.2-17.3)	1580 (1245-2240)	1295 (1020-1630)	720 (580-920)	51 (0-290)	9.3 (6.8-12.0)	11.2 (9.3-13.0)
rFP	14.6 (10.2-17.5)	1350 (915-1930)	1295 (1020-1630)	550 (420-750)	40 (0-174)	10.9 (7.9-16.4)	11.3 (9.4-13.1)
rFP+ mung	17.4 (13.4-21.5)	1745 (1380-2530)	1545 (1240-1860)	535 (390-750)	40 (0-174)	10.1 (7.1-12.5)	11.2 (9.6-12.2)
20 June Sowing (D3)							
FP	12.5 (6.4-16.5)	1610 (1275-2050)	1310 (1080-1525)	810 (630-1130)	46 (0-260)	7.9 (3.5-11.9)	9.5 (4.9-12.3)
rFP	12.5 (6.4-16.6)	1410 (1155-1770)	1315 (1085-1525)	650 (460-930)	39 (0-200)	9.0 (4.1-13.4)	9.5 (4.9-12.4)
rFP+ mung	15.3 (8.3-19.6)	1685 (1300-2145)	1500 (1225-1815)	630 (410-780)	39 (0-200)	9.2 (4.7-13.4)	10.2 (5.8-12.7)
15 July Sowing (D4)							
FP	5.7 (2.5-9.2)	1720 (1300-1995)	1250 (1050-1445)	995 (750-1350)	40 (0-235)	3.3 (1.5-4.7)	4.5 (2.3-6.5)
rFP	5.7 (2.5-9.2)	1510 (1110-1765)	1250 (1050-1445)	830 (590-1200)	31 (0-180)	3.7 (1.7-5.4)	4.5 (2.3-6.5)
rFP+ mung	8.3 (4.8-13.0)	1700 (1255-2150)	1370 (1080-1680)	775 (580-1010)	31 (0-180)	4.9 (2.7-6.8)	6.1 (3.7-7.8)

2b. Medium duration variety (PAU201)

	Rice equivalent yield (t ha⁻¹)	Irrigation (mm)	ET (mm)	Drainage (mm)	Runoff (mm)	WPI (kg ha⁻¹mm⁻¹)	WPet (kg ha⁻¹mm⁻¹)
15 May Sowing (D1)							
FP	12.8 (8.3-15.4)	1380 (1020-1965)	1170 (885-1470)	620 (520-830)	50 (0-200)	9.4 (7.1-12.8)	10.9 (9.2-12.6)
rFP	13.0 (8.5-15.6)	1195 (855-1670)	1175 (885-1480)	480 (360-710)	40 (0-172)	10.9 (8.4-15.5)	11.0 (9.3-12.7)
rFP+mung	14.4 (10.8-19.1)	1675 (1335-2350)	1440 (1135-1760)	470 (330-675)	40 (0-172)	9.0 (7.0-11.1)	10.4 (8.6-12.3)
5 June Sowing (D2)							
FP	13.1 (8.8-15.8)	1380 (970-1885)	1185 (920-1445)	660 (515-860)	48 (0-260)	9.6 (7.5-11.8)	11.1 (9.2-13.2)
rFP	13.1 (8.7-15.7)	1180 (869-1640)	1185 (920-1445)	505 (380-690)	36 (0-172)	11.4 (8.8-16.0)	11.2 (9.3-13.3)
rFP+ mung	16.7 (12.1-20.4)	1630 (1280-2300)	1470 (1170-1750)	500 (380-705)	36 (0-172)	10.4 (7.7-12.7)	11.4 (10.1-12.8)
20 June Sowing (D3)							
FP	13.8 (9.7-16.8)	1440 (1125-1855)	1240 (1015-1435)	730 (550-1060)	45 (0-270)	9.6 (7.5-12.1)	11.1 (9.5-13.0)
rFP	13.8 (9.7-16.8)	1245 (900-1625)	1240 (1015-1440)	575 (380-830)	37 (0-170)	11.3 (9.0-15.8)	11.1 (9.6-12.9)
rFP+ mung	16.9 (12.6-20.6)	1555 (1130-2060)	1450 (1165-1750)	555 (360-785)	37 (0-170)	11.0 (8.8-14.5)	11.6 (10.5-12.7)
15 July Sowing (D4)							
FP	8.7 (4.3-12.7)	1575 (1300-1995)	1240 (1050-1445)	900 (620-1285)	33 (0-230)	5.6 (2.9-8.8)	7.0 (3.9-10.0)
rFP	8.7 (4.3-12.7)	1355 (1000-1640)	1245 (1055-1450)	730 (545-970)	30 (0-176)	6.5 (3.4-10.4)	7.0 (3.9-10.0)
rFP+ mung	11.3 (7.0-16.2)	1565 (1140-1875)	1350 (1095-1645)	660 (455-830)	30 (0-176)	7.3 (4.3-10.7)	8.4 (5.8-11.7)

2c. Short duration variety (PR115)

	Rice equivalent yield (t ha ⁻¹)	Irrigation (mm)	ET (mm)	Drainage (mm)	Runoff (mm)	WPI (kg ha ⁻¹ mm ⁻¹)	WPet (kg ha ⁻¹ mm ⁻¹)
15 May Sowing (D1)							
FP	11.9 (8.8-14.2)	1330 (1065-1800)	1060 (800-1360)	660 (475-880)	40 (0-200)	9.0 (7.1-11.6)	11.2 (9.4-13.2)
rFP	11.9 (8.8-14.2)	1130 (830-1560)	1060 (800-1370)	510 (330-710)	22 (0-200)	10.6 (8.2-13.4)	11.2 (9.3-13.1)
rFP+ mung	13.8 (9.6-17.6)	1610 (1210-2240)	1325 (1065-1635)	495 (285-690)	22 (0-200)	8.7 (6.7-11.1)	10.4 (8.1-12.3)
5 June Sowing (D2)							
FP	11.9 (8.3-14.3)	1240 (935-1750)	1040 (780-1300)	630 (510-815)	45 (0-170)	9.7 (7.5-12.6)	11.4 (9.3-13.1)
rFP	11.8 (8.2-14.2)	1040 (675-1510)	1040 (780-1305)	490 (365-655)	34 (0-170)	11.5 (8.7-17.5)	11.4 (9.3-13.1)
rFP+ mung	15.3 (11.5-18.5)	1420 (1105-2020)	1330 (1030-1625)	460 (340-630)	34 (0-170)	10.8 (8.7-13.0)	11.4 (9.8-12.6)
20 June Sowing (D3)							
FP	11.9 (7.4-14.4)	1240 (880-1740)	1070 (830-1280)	670 (520-975)	50 (0-220)	9.6 (7.0-12.4)	11.0 (8.8-12.8)
rFP	11.9 (7.3-14.4)	1035 (710-1510)	1075 (835-1285)	530 (400-775)	41 (0-160)	11.5 (8.6-16.6)	10.9 (8.7-12.6)
rFP+ mung	15.2 (10.3-19.2)	1360 (960-1945)	1310 (990-1550)	500 (380-690)	41 (0-160)	11.3 (8.4-14.8)	11.5 (9.5-12.7)
15 July Sowing (D4)							
FP	12.3 (8.7-15.5)	1370 (1035-1730)	1150 (955-1310)	780 (550-1160)	45 (0-225)	9.3 (7.0-12.1)	10.9 (8.8-13.1)
rFP	12.3 (8.7-15.4)	1165 (865-1500)	1150 (960-1310)	640 (460-855)	35 (0-110)	10.8 (8.4-14.4)	10.8 (8.7-13.0)
rFP+ mung	15.5 (11.5-19.2)	1450 (1090-1890)	1295 (1060-1580)	590 (435-790)	35 (0-110)	10.8 (8.5-14.0)	12.0 (10.9-13.0)

Fig. 1. Evaluation of the APSIM model for simulation of rice yield using independent data for PR115 and PR118 from the experiments of Yadvinder-Singh et al. (2009) on a sandy loam soil

Fig. 2. Evaluation of APSIM for volumetric water content (VWC) in 3 soil layers to 60 cm depth for a rice-wheat cropping system using the data of Humphreys et al. (2008) on a sandy loam soil. Lines are simulated data, open circles are observed data .

Figs 3a,b. The effect of rice sowing date (D1-D4) and rice variety duration (long, medium, short) on yield in a rice-wheat system using farmers' practice (FP). Yield of rice and wheat (a), and mungbean (b). Vertical shaded bars are 5th-95th percentiles, black dots show the range and triangle represents median values over 40 years (1970-2010). Sowing dates are 15 May (D1), 5 June (D2), 20 June (D3), 15 July (D4).

Figs 4a,b. The effect of rice sowing date (D1-D4) and rice variety duration (long, medium, short) on irrigation in rice-wheat systems using farmers' practice (FP) or recommended farmers' practice (rFP). Irrigation of rice (a), and wheat and mungbean (b). Vertical shaded bars are 5th-95th percentiles, black dots show the range and triangle represents median values over 40 years (1970-2010). Sowing dates are 15 May (D1), 5 June (D2), 20 June (D3), 15 July (D4).

Figs 5a,b. The effect of rice sowing date (D1-D4) and rice variety duration (long, medium, short) on drainage in rice-wheat systems using farmers' practice (FP) or recommended farmers' practice (rFP). Drainage of rice (a), and wheat and fallow (after wheat harvest) (b), Vertical shaded bars are 5th-95th percentiles, black dots show the range and triangle represents median values over 40 years (1970-2010). Sowing dates are 15 May (D1), 5 June (D2), 20 June (D3), 15 July (D4).

Figs 6a,b. The effect of rice sowing date (D1-D4) and rice variety duration (long, medium, short) on evapotranspiration (ET) in a rice-wheat system using farmers' practice (FP). ET of rice and wheat (a), and fallow and mungbean ET (b). Vertical shaded bars are 5th-95th percentiles, black dots show the range and triangle represents median values over 40 years (1970-2010). Sowing dates are 15 May (D1), 5 June (D2), 20 June (D3), 15 July (D4).

Fig. 7. The effect of rice sowing date (D1-D4) and rice variety duration (long, medium, short) on water productivity based on evapotranspiration (WPet) in a rice-wheat system using farmers' practice (FP). Vertical shaded bars are 5th-95th percentiles, black dots show the range and triangle represents median values over 40 years (1970-2010). Sowing dates are 15 May (D1), 5 June (D2), 20 June (D3), 15 July (D4).

Figs 8a,b. The effect of rice sowing date (D1-D4) and rice variety duration (long, medium, short) on water productivity based on irrigation (WPI) in rice-wheat systems using farmers' practice (FP) or recommended farmers' practice (rFP). WPI of rice (a), and wheat and mungbean (b). Vertical shaded bars are 5th-95th percentiles, black dots show the range and triangle represents median values over 40 years (1970-2010). Sowing dates are 15 May (D1), 5 June (D2), 20 June (D3), 15 July (D4).